

The 2015 RHIC/AGS Annual Users' Meeting

The Perfect Liquid at RHIC:
A Decade of Discovery

Gluon Polarization in Longitudinally Polarized pp Collisions at STAR

June 9-12, 2015

Brookhaven National Laboratory

Topical workshops // June 9-10

Plenary sessions and Perfect Liquid 10-year Celebration // June 11-12

Special guest speaker AAAS Chief Executive Officer and former Congressman Rush Holt

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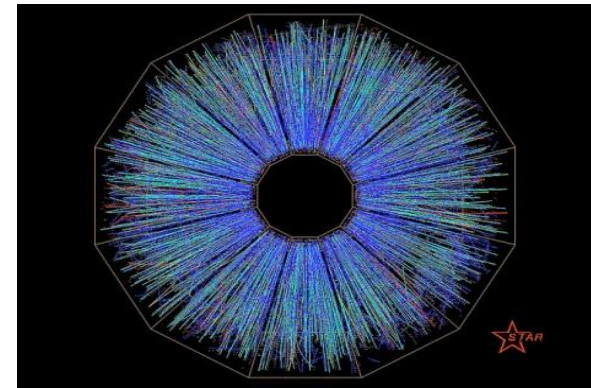
Register at www.bnl.gov/aum2015

Poster designed by Chenxin Yang **Pratt**

RHIC/AGS USERS' CENTER

Zilong Chang

For STAR Collaboration



TEXAS A&M
UNIVERSITY

Outline

- ☐ Introduction
- ☐ Inclusive jet measurements
- ☐ π^0 measurements
- ☐ Di-jet measurements
- ☐ Conclusion



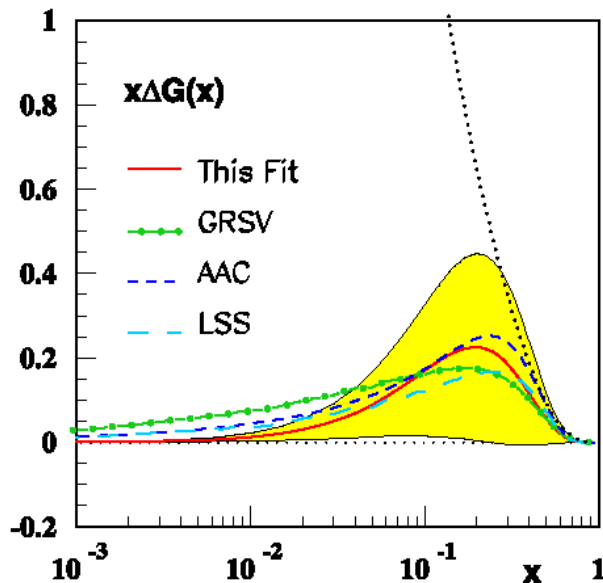
How Gluons Contribute to Proton Spin

Proton Spin:

$$S_z = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

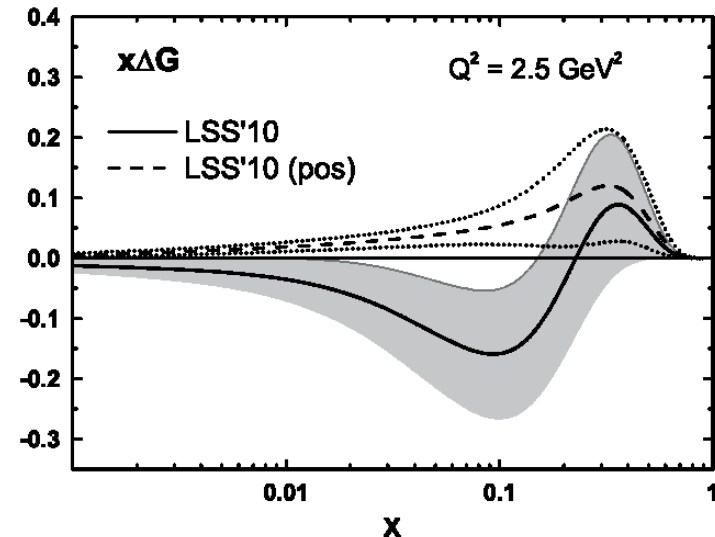
- $\Delta\Sigma$: ~ 0.3 measured by DIS
- ΔG : poorly determined by DIS and SIDIS
- L_q, L_g : undetermined yet.

➤ Blümlein & Böttcher, NPB 841, 205 (2010) with fit to DIS data only



- $\Delta G = 0.46 \pm 0.43$

➤ Leader et al, PRD 82, 114018 (2010) with fit to DIS and SIDIS data



- LSS'10p: $\Delta G = 0.32 \pm 0.19$
- LSS'10: $\Delta G = -0.34 \pm 0.46$

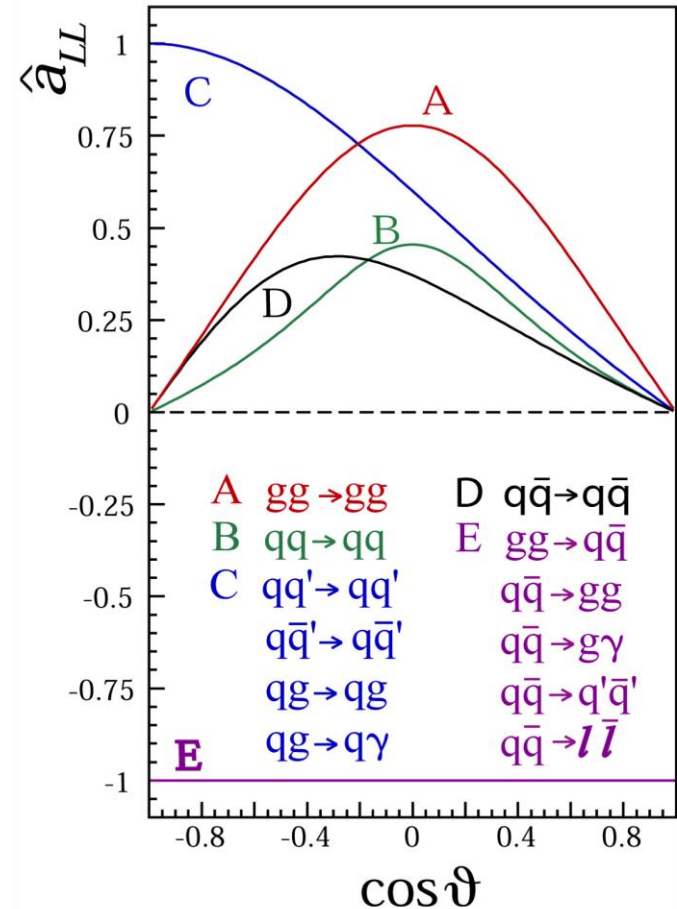
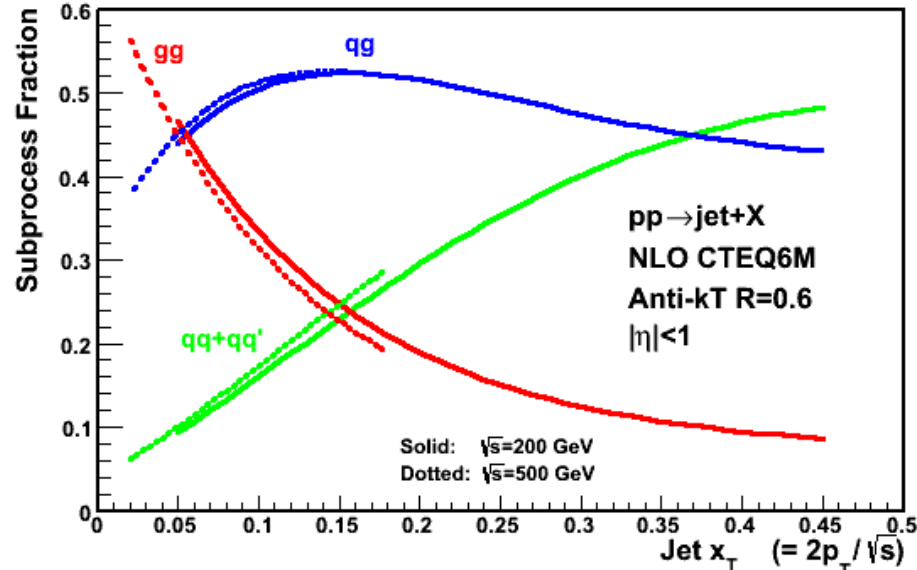
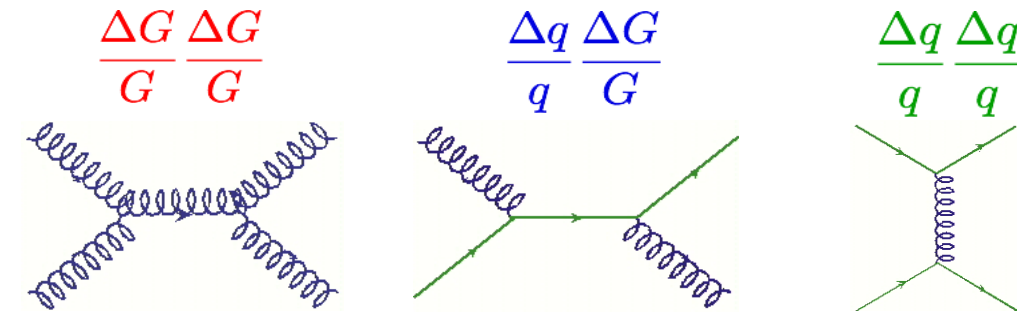


Exploring Gluon Contribution at RHIC

Double spin asymmetry A_{LL} :

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \propto \frac{\Delta f_a \Delta f_b}{f_a f_b} \hat{a}_{LL}$$

Δf : polarized parton distribution function



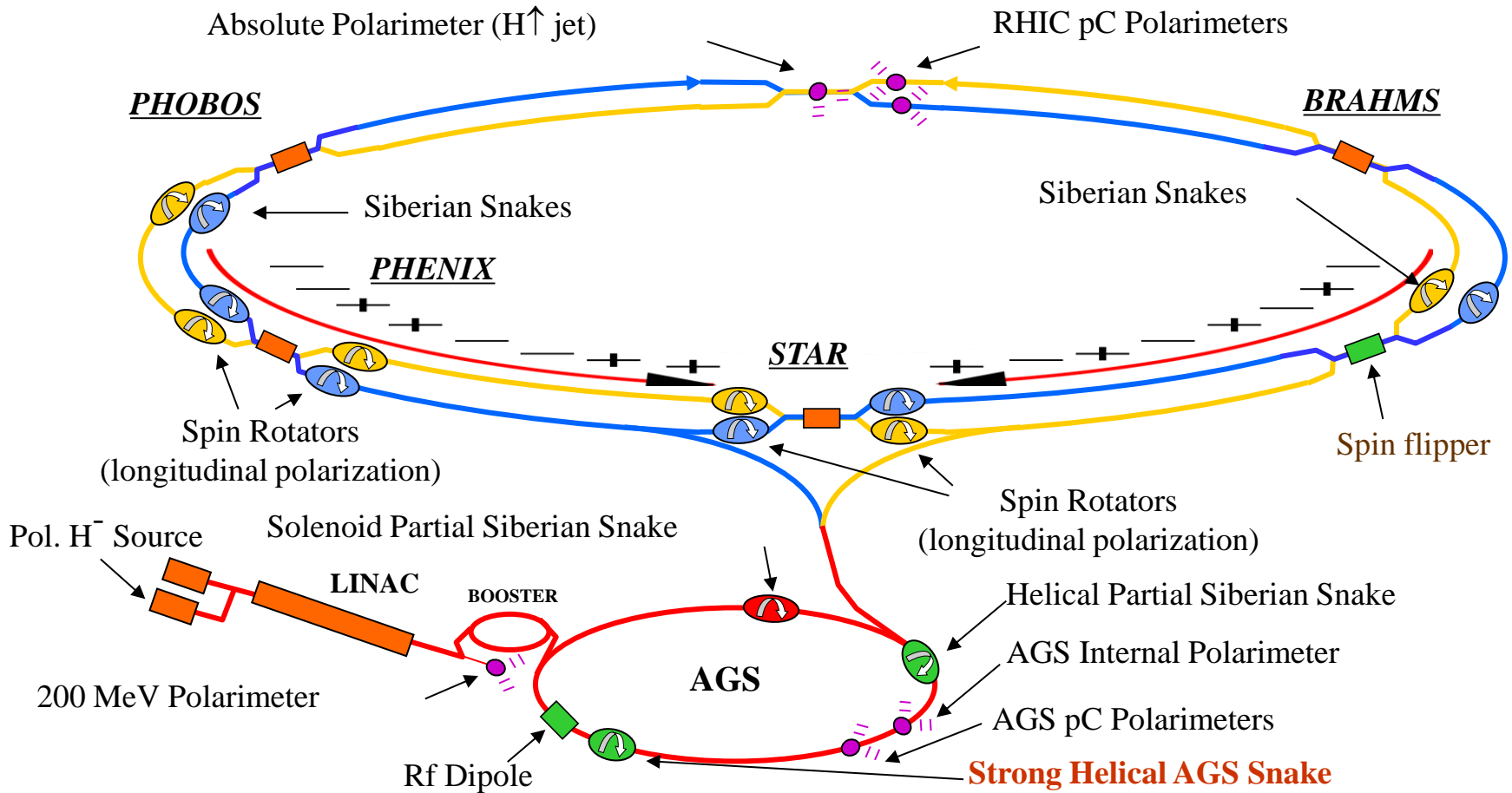
For most RHIC kinematics, **gg** and **qq** **dominate**, making A_{LL} for jets and π^0 sensitive to gluon polarization

Mukherjee and Vogelsang, PRD.86.094009

The RHIC/AGS Annual Users Meeting -- Z. Chang 06/09/2015



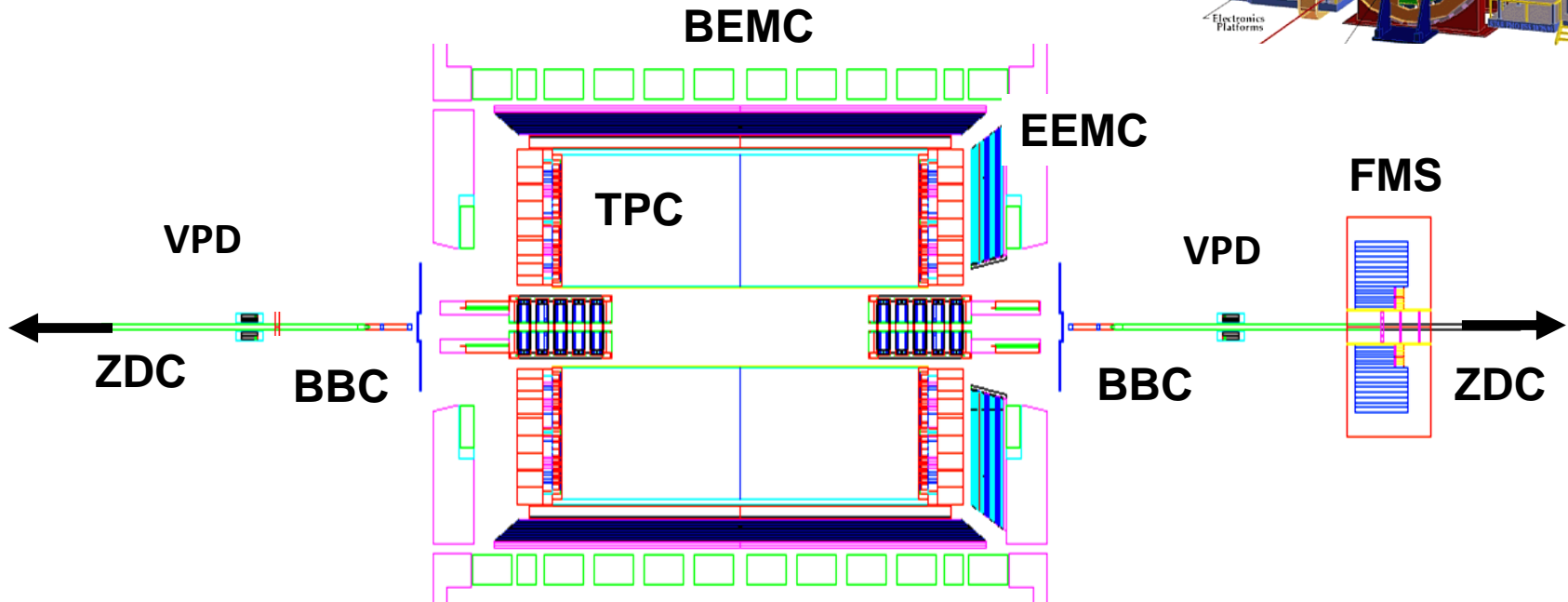
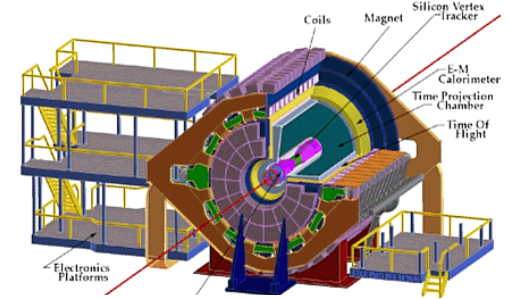
RHIC Facilities



- Spin varies from rf bucket to rf bucket (9.4 MHz)
- Spin pattern changes from fill to fill
- Spin rotators provide choice of spin orientation
- Billions of spin reversals during a fill with little depolarization



STAR Detectors



- High precision tracking with **Time Projection Chamber**
- High energy resolution with **Barrel Electro-Magnetic Calorimeter, Endcap Electro-Magnetic Calorimeter and Forward Meson Spectrometer**
- Additional detectors (**Beam-Beam Counter, Vertex Position Detector, and Zero Degree Calorimeter**) for relative luminosity and local polarimetry



STAR Experiment Unique Access to Gluon Polarization

Longitudinally polarized pp collisions at 200 GeV and 510 GeV allow both cross section and double spin asymmetry A_{LL} measurements on:

❖ Inclusive Jet

x down to ~ 0.05 for jets in the mid-rapidity at 200 GeV (x down to ~ 0.02 at 510 GeV)

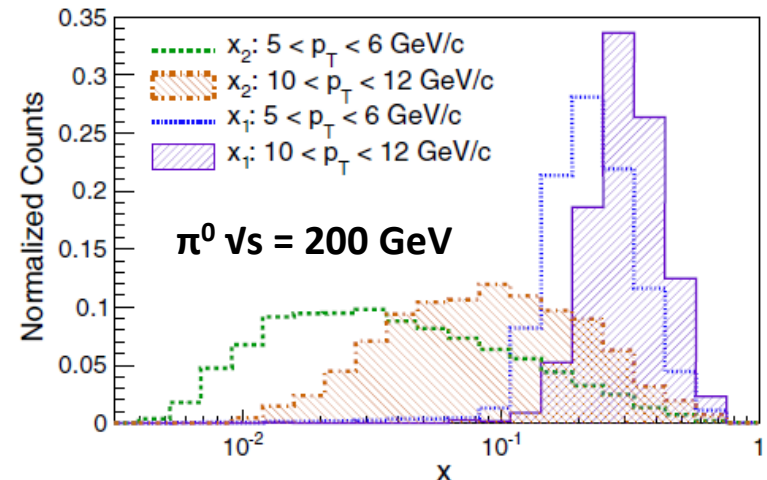
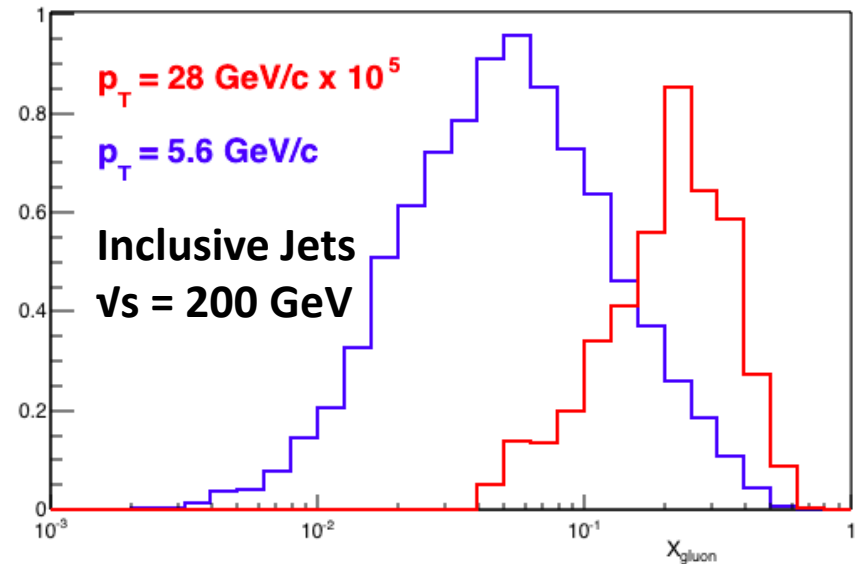
❖ Inclusive π^0

x down to ~ 0.02 for forward π^0
 $0.8 < |\eta| < 2.0$ at 200 GeV

❖ Di-jet

Correlation unfolds x_1, x_2 at the leading order

Complementary to each other to achieve large x_g coverage of gluon polarization



☒ Inclusive jet measurements

☐ π^0 measurements

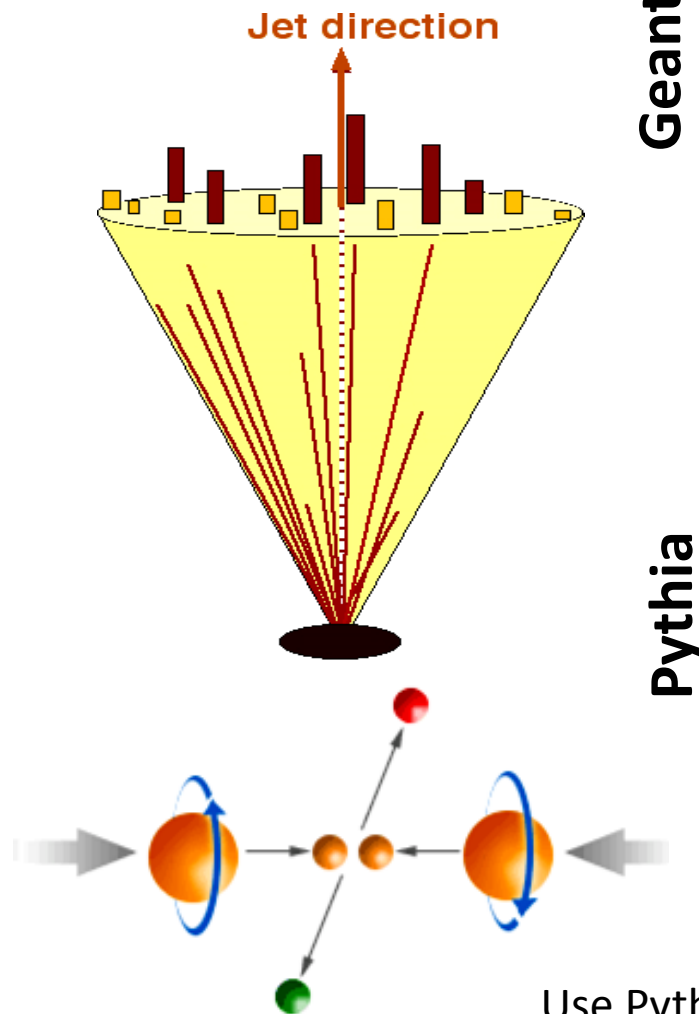
☐ Di-jet measurements

Jet Reconstruction at STAR

Detector

Particle

Parton



Geant

Pythia

- For 2006 200 GeV data (see back-up)
Mid-point cone algorithm
Adapted from Tevatron II – hep-ex/0005012
 - a. Seed energy = 0.5 GeV
 - b. Cone radius $R = 0.7$ in η - ϕ space
 - c. Split/merge fraction $f = 0.5$
- For 2009 200 GeV data
Anti- k_T algorithm
Cacciari, Salam, and Soyez, JHEP 0804, 063
 - Jet parameter **$R = 0.6$**
- For 2012 510 GeV data
Anti- k_T algorithm
 - Jet parameter **$R = 0.5$**

Use Pythia + Geant to quantify detector response

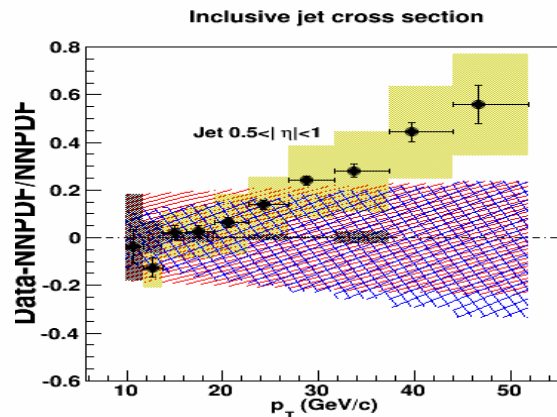
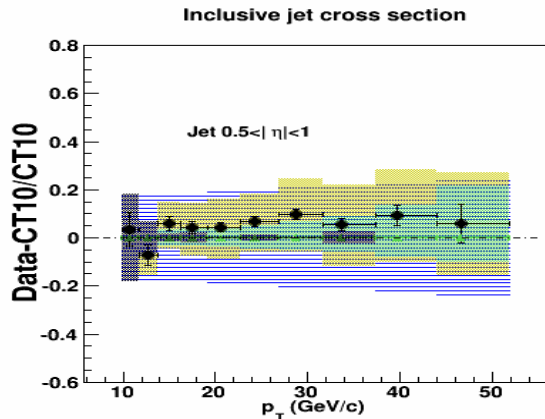
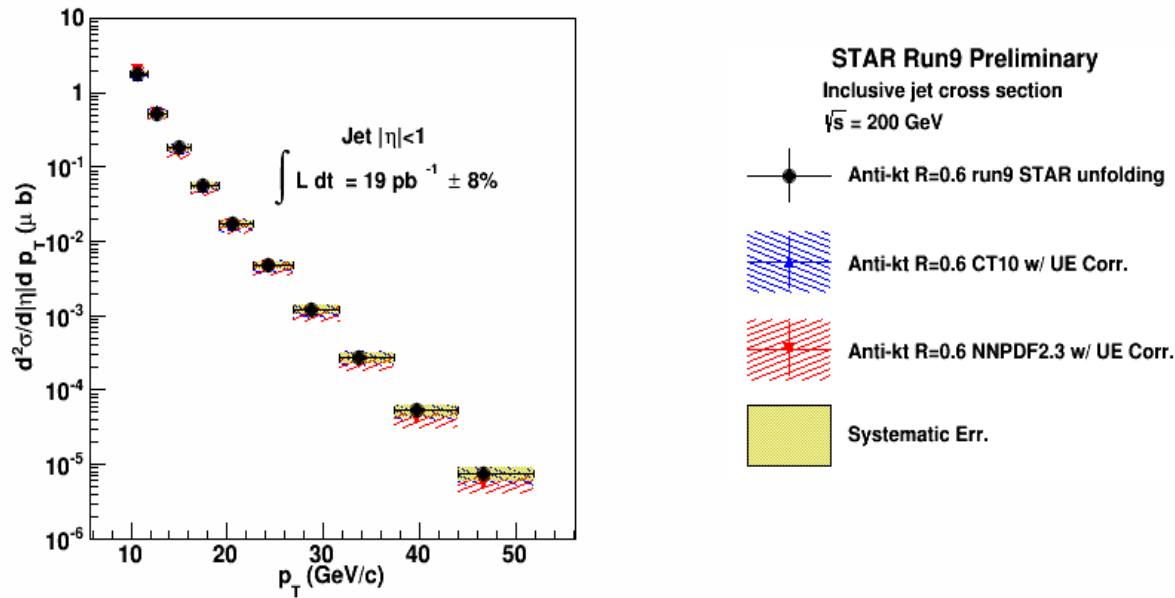
Sjostrand, Mrenna, and Skands, JHEP 05, 026



Inclusive Jet Cross Section from 2009 Data

➤ X. Li for the STAR collaboration, DIS 2015

Inclusive jet cross section

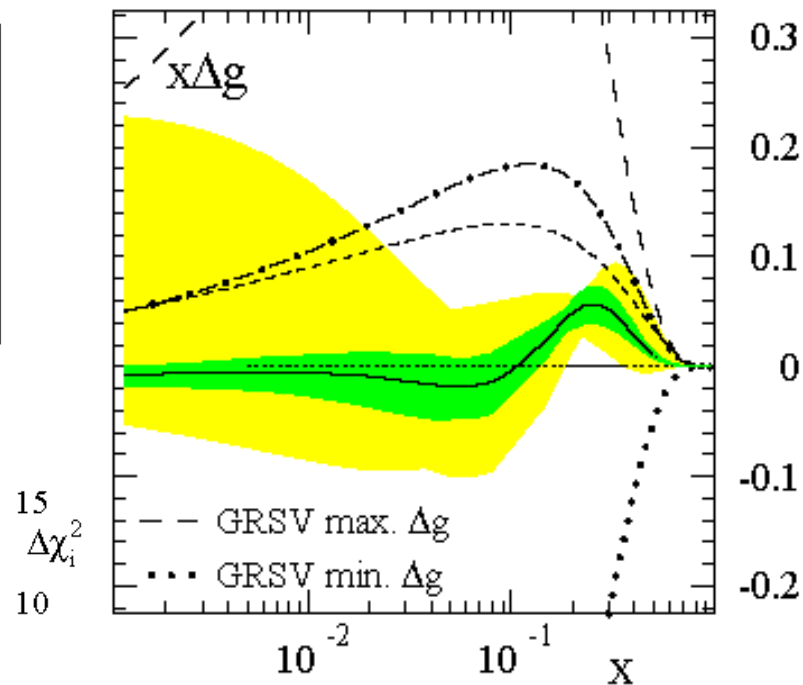
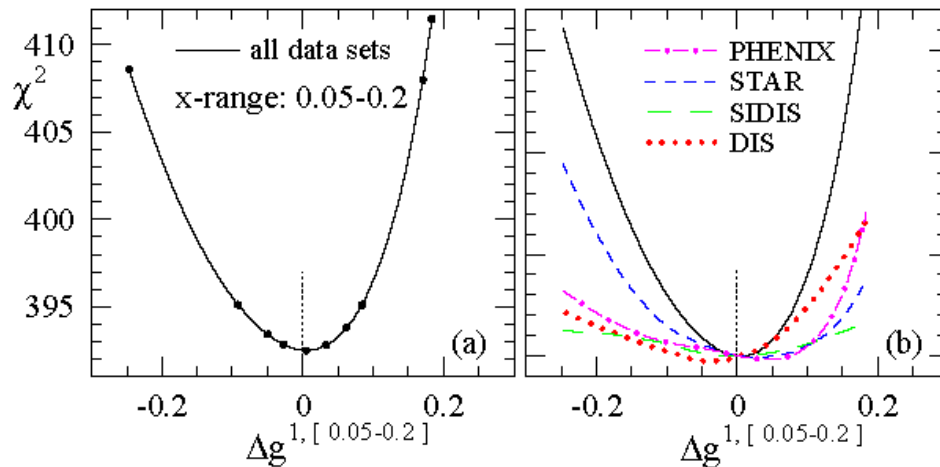
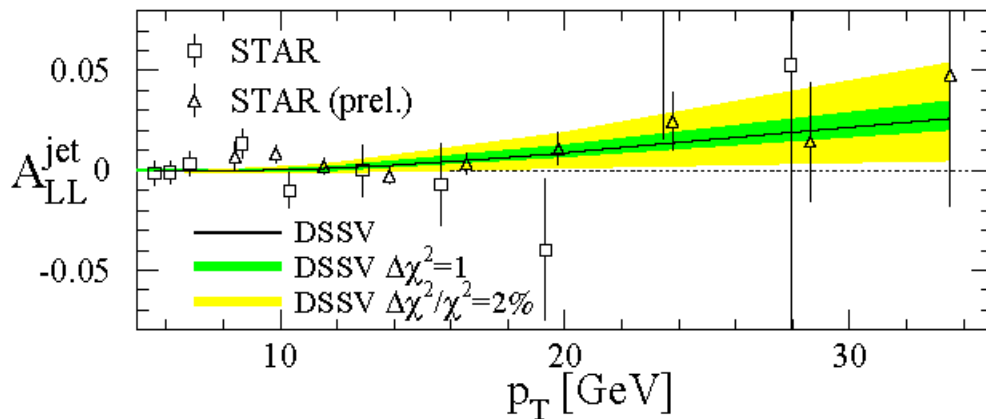


- Good agreement with several NLO pQCD calculations after hadronization and underlying event correction is applied
- Inclusive jet cross sections also calculated in two sub η ranges $0 < |\eta| < 0.5$ and $0.5 < |\eta| < 1.0$
- Jet production well understood at STAR



DSSV – First Global Analysis with Polarized Jets Data

➤ de Florian et al., PRL 101, 072001



- The first global NLO analysis to include inclusive DIS, SIDIS, and **RHIC pp data** on an equal footing
- Found relatively **small gluon polarization** within the region $0.05 < x < 0.2$ that was sampled by the STAR 2006 data



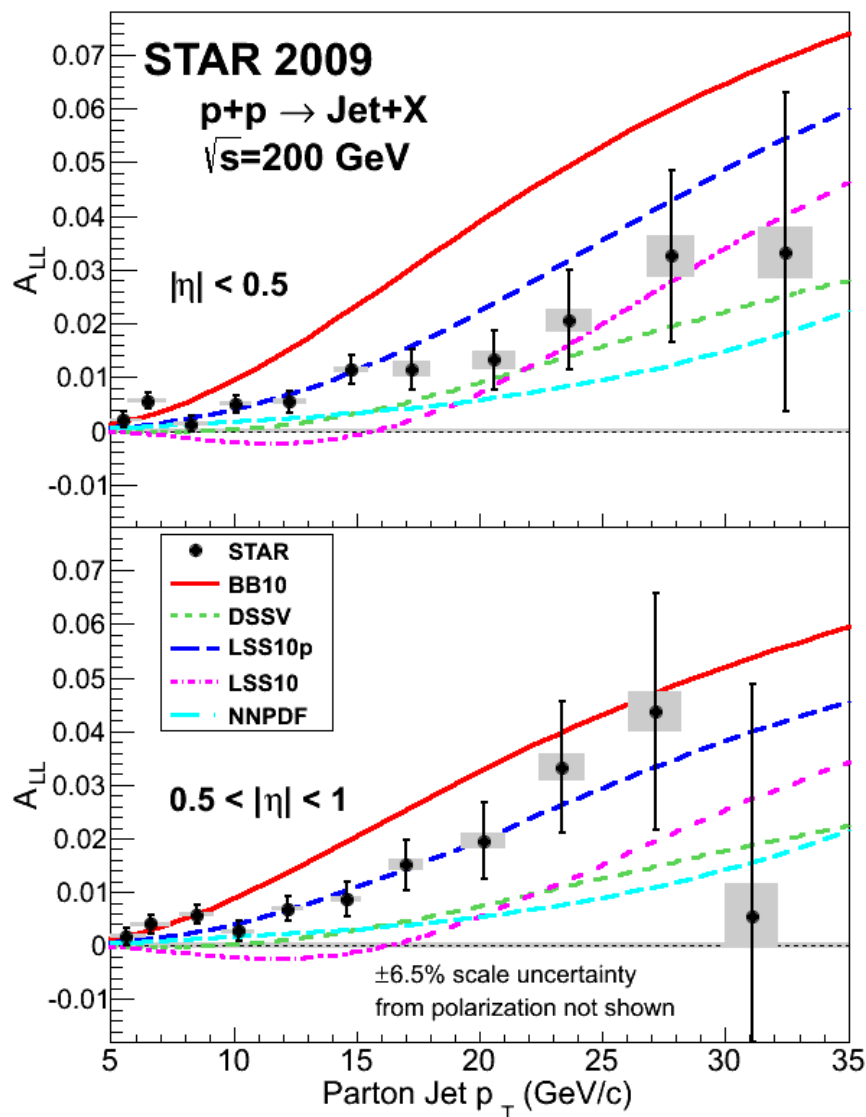
Improvements for 2009

- **2009 jet patch trigger upgrades**
 - Overlapping jet patches and lower E_T threshold improve efficiency and reduce trigger bias
 - Net increase of 37% in jet acceptance
 - Remove beam-beam counter trigger requirement
 - Trigger more efficiently at high jet p_T
 - Measure non-collision background
- **Increased trigger rate and reduced thresholds enabled by DAQ1000**
- **Sampled ~ 4 times the figure-of-merit relative to 2006**
- **Nearly 20-fold increase in event statistics**
- **Improvements in jet reconstruction**
 - Subtract 100% of track momentum from struck tower energy (2009) instead of MIP (2006)
 - Overall jet energy resolution improved from 23% to 18%
 - Switch from mid-point cone with cone radius 0.7 to anti- k_T with jet parameter 0.6 (a. less susceptible to soft diffusion and underlying events; b. increase in statistics)

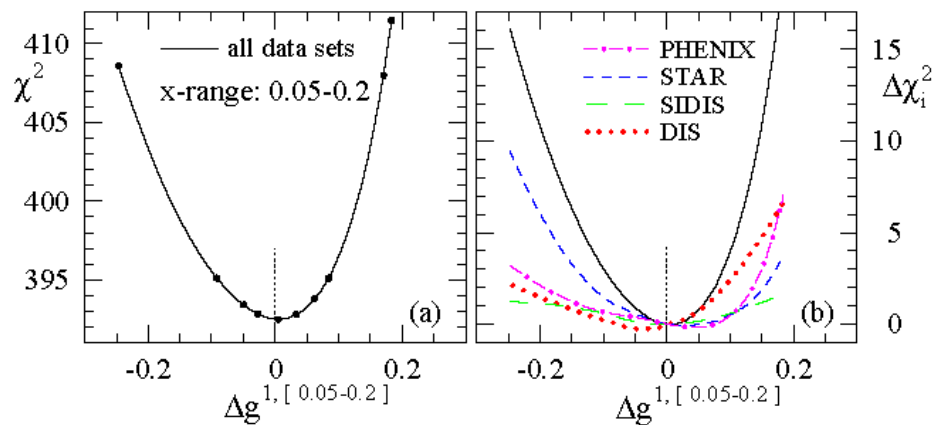


Inclusive Jet A_{LL} from 2009 Data

➤ arXiv:1405.5134

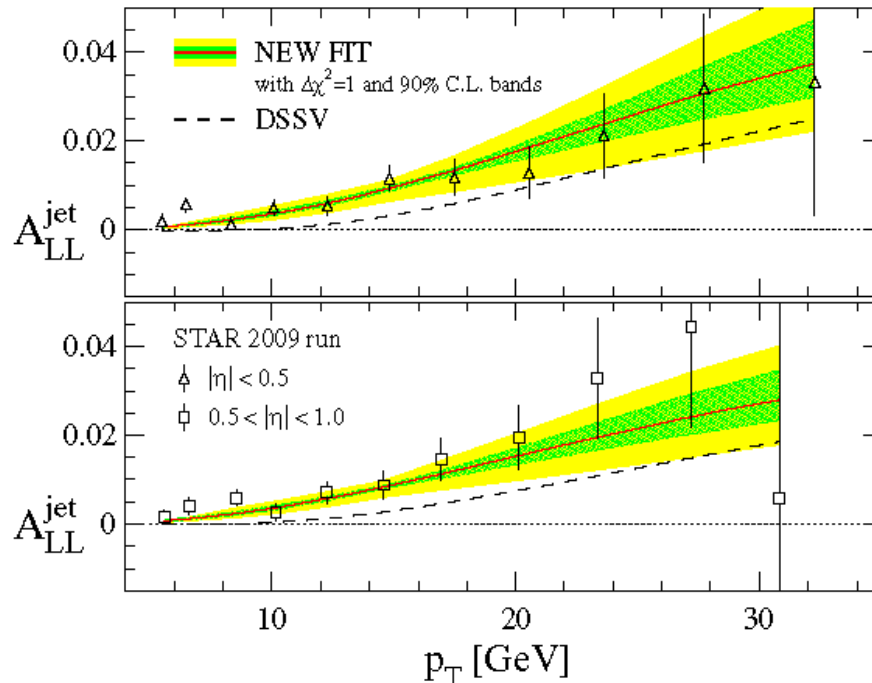


- 2009 STAR inclusive jet A_{LL} measurements are a factor of 3 (high- p_T) to >4 (low- p_T) more precise than 2006
- A_{LL} falls in the middle among several recent polarized PDF fit predictions
- A_{LL} is somewhat larger than predictions from the **2008 DSSV** fit
 - Points toward positive Δg in the accessible x region

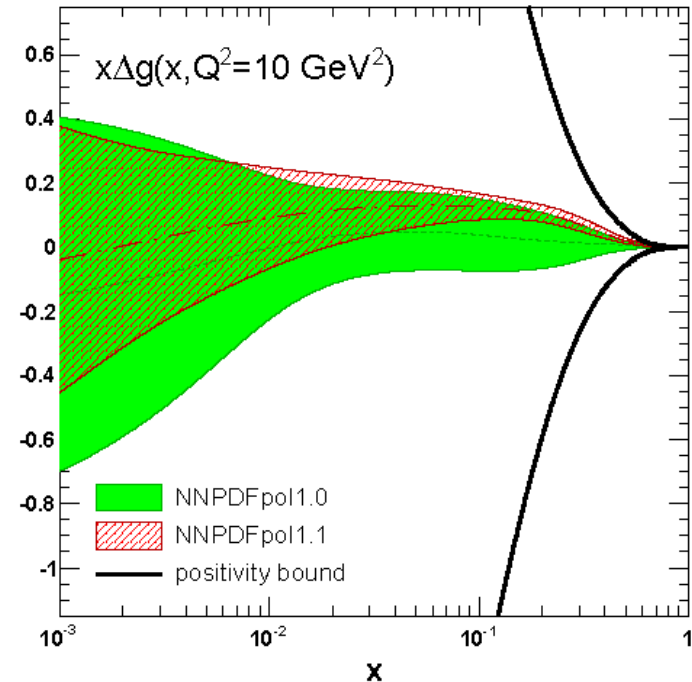


Two New Polarized Distribution Fits

➤ DSSV, PRL 113, 012001



➤ NNPDF, NPB 887.276



- Both DSSV and NNPDF have released new polarized PDF fits
- Both find 2009 STAR jet A_{LL} results provide significantly tighter constraints on gluon polarization than previous measurements
- Both find evidence for positive gluon polarization in the region $x > 0.05$
 - DSSV: $0.19^{+0.06}_{-0.05}$ at 90% C.L. for $x > 0.05$
 - NNPDF: 0.23 ± 0.07 for $0.05 < x < 0.5$

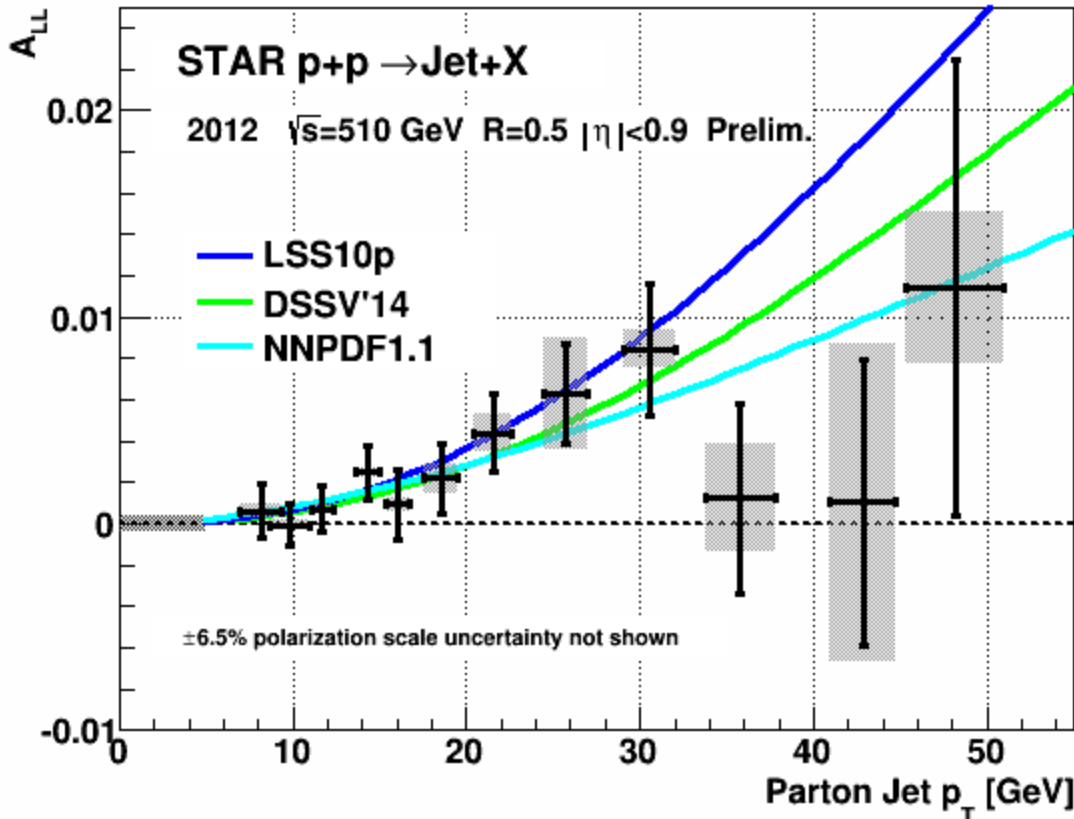


2012 pp 510 GeV Run

- **510 GeV longitudinally polarized pp collisions**
 - average polarization 53%
 - analysis of data of integrated luminosity 50 pb^{-1}
- **510 GeV provides sensitivity to smaller x_g**
- **Same jet reconstruction method except using smaller cone radius $R = 0.5$**
 - Reduced pile-up effects
 - Better matching probability from detector jet to parton jet
- **$|\eta| < 0.9$**
 - Narrower vertex distribution in 2012
- **Non-collision background and transverse residual double spin asymmetry found to make negligible contributions**



2012 Inclusive Jet A_{LL}

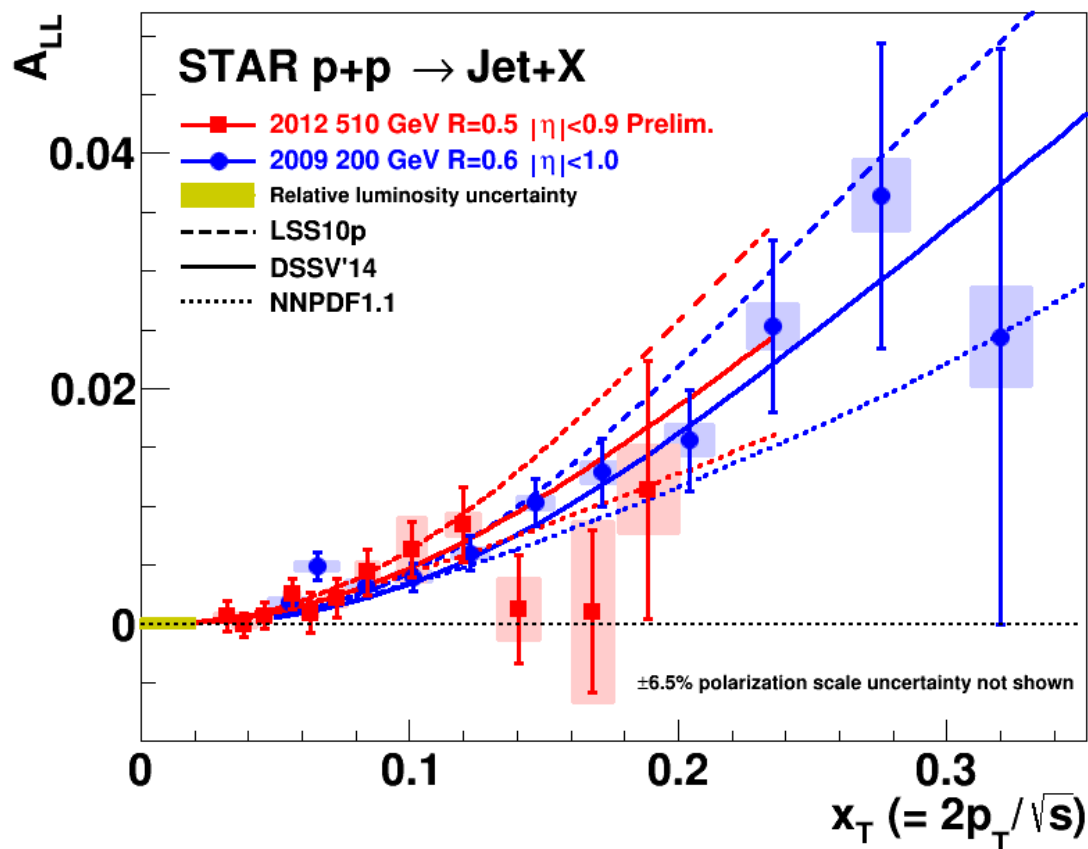


- Trigger and reconstruction bias dominates the systematic uncertainties
- Relative luminosity systematic uncertainty is 4×10^{-4}
- Results agree well with latest NLO predictions

**systematics will be reduced in the final results (coming soon)*



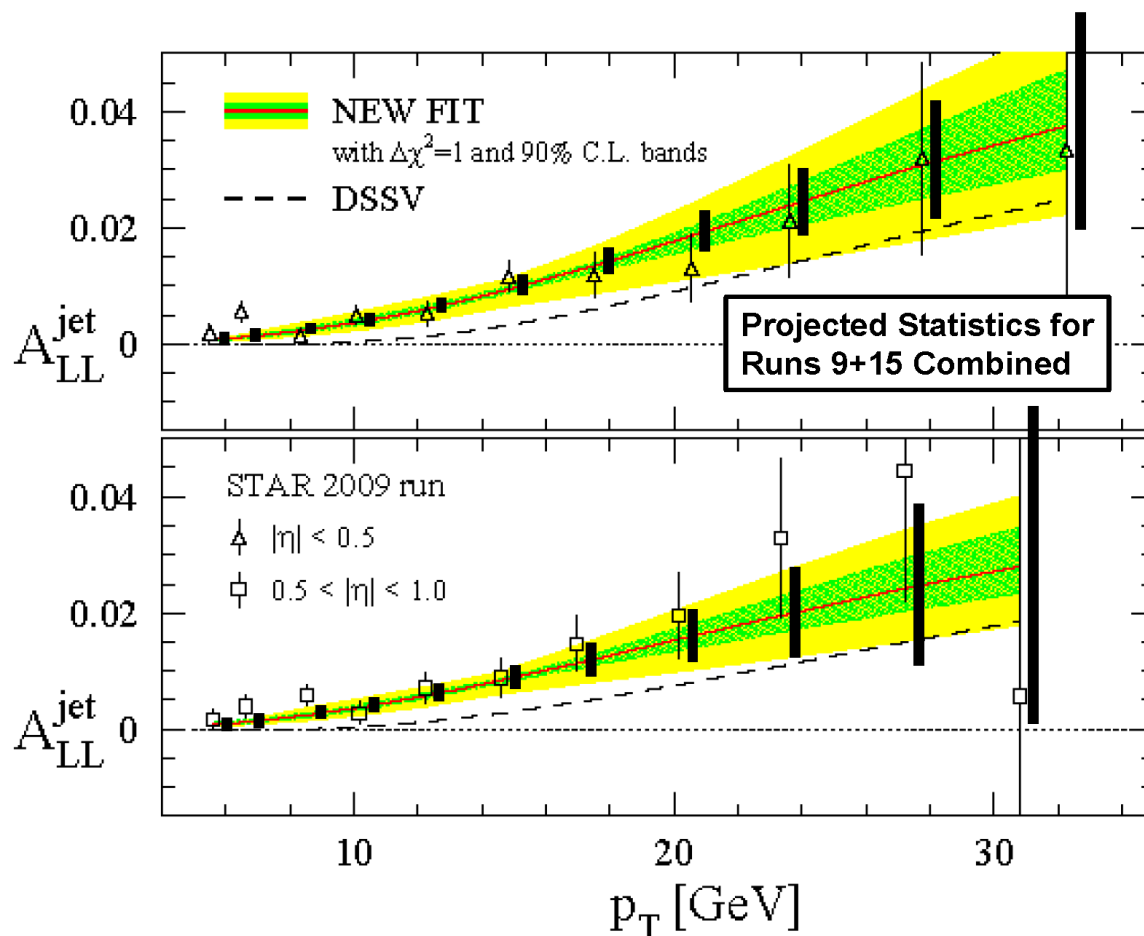
2012 Inclusive Jet A_{LL} with 2009 Data



- Higher collision energy extends $x_T = 2p_T/\sqrt{s}$ to lower region
- 510 GeV results agree well with 200 GeV data in the overlapping x_T region



Increased Precision at 200 GeV Coming Soon



- STAR also anticipates significant future reductions in the uncertainties for 200 GeV collisions relative to the 2009 results thanks to the RHIC 2015 run



☐ Inclusive jet measurements

☒ π^0 measurements

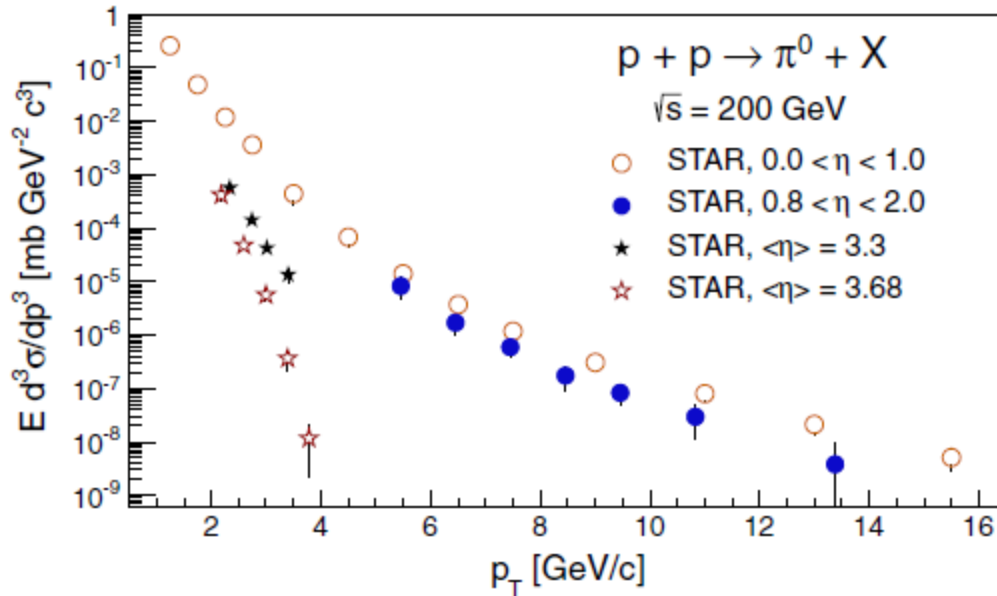
☐ Di-jet measurements



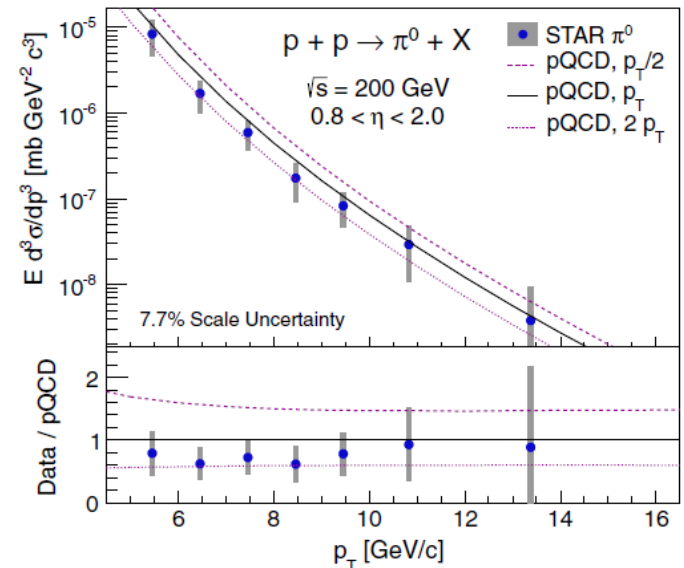
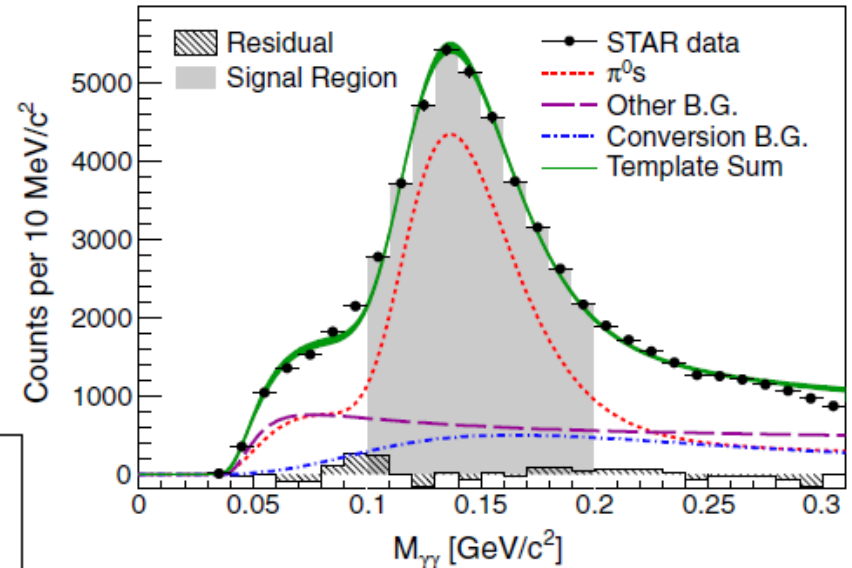
π^0 Measurements at STAR

➤ PRD.89.012001

- Studied π^0 production at $0.8 < \eta < 2$ in 200 GeV pp collisions from 2006 data
- Measure γ from π^0 decay in electromagnetic calorimeter

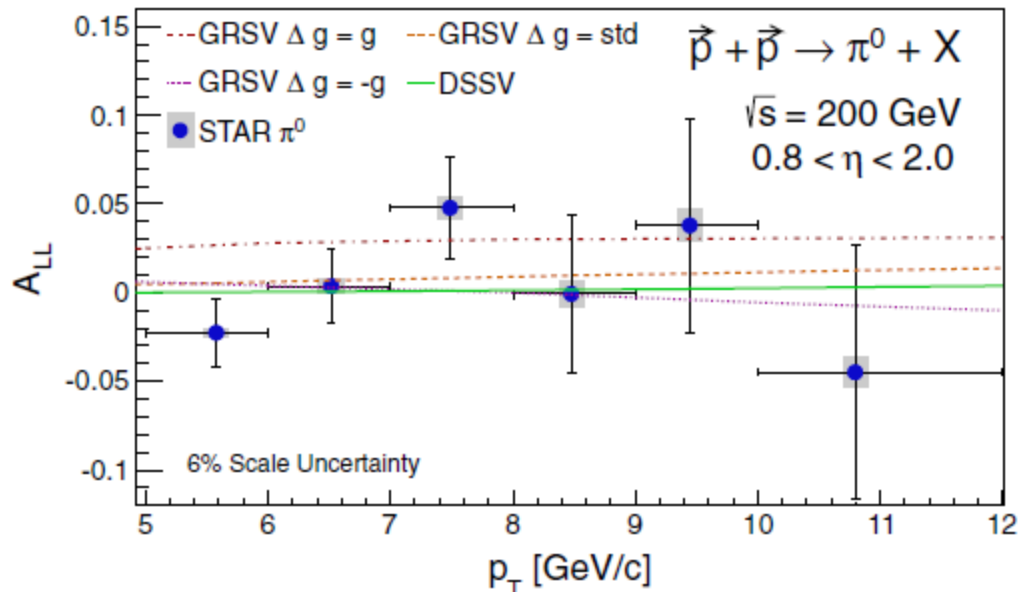


- STAR has measured the inclusive π^0 cross section over a wide pseudo-rapidity range

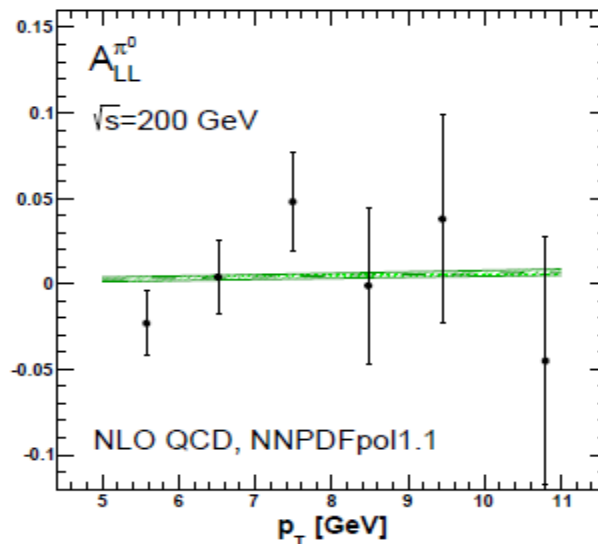


Inclusive π^0 Double Spin Asymmetry A_{LL}

➤ PRD.89.012001



➤ NPB 887.276: NNPDFpol1.1 prediction with STAR 200 GeV data ($0.8 < \eta < 2.0$)

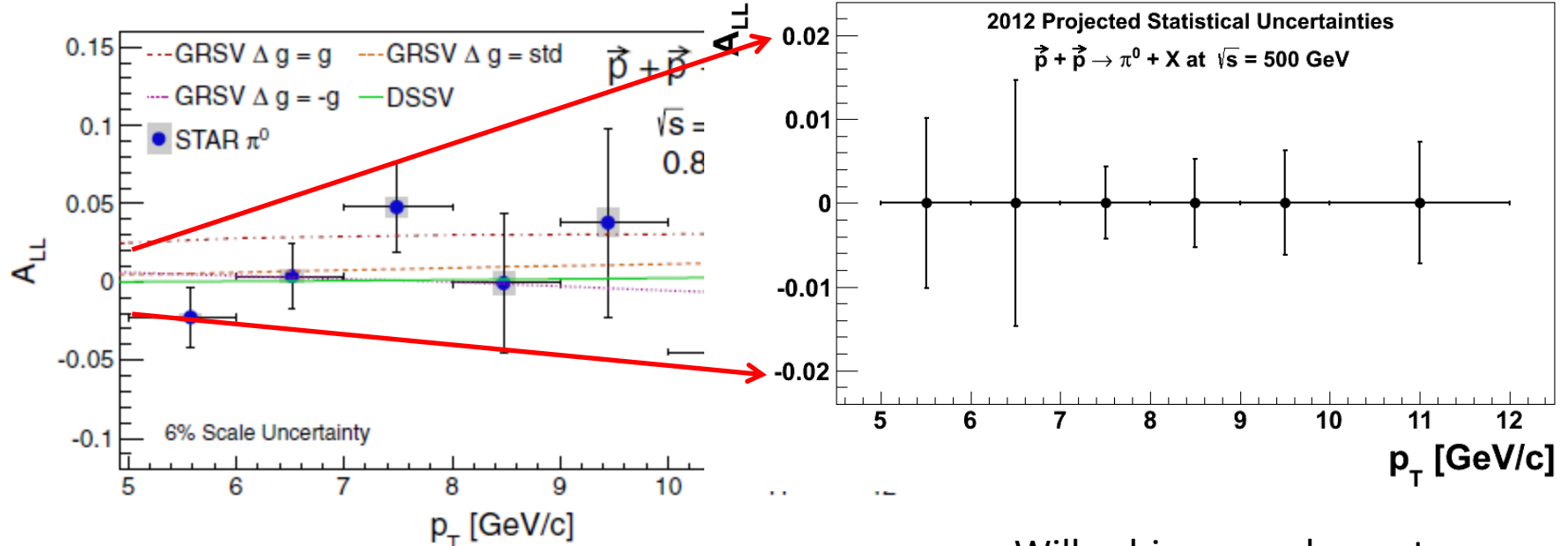


- Needs greater precision to constrain NLO fit

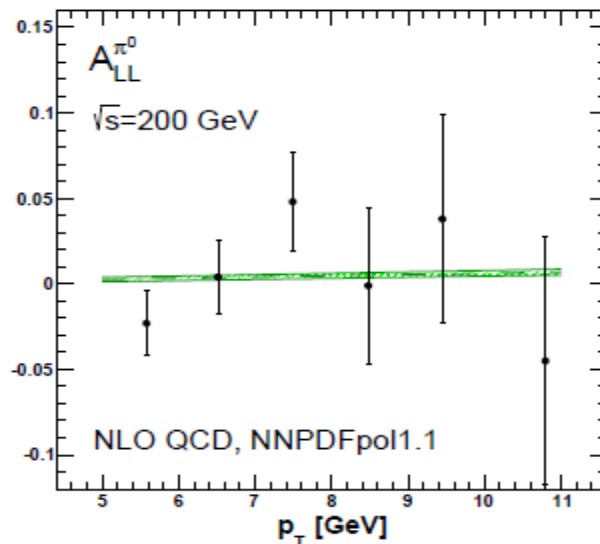


Inclusive π^0 Double Spin Asymmetry A_{LL}

➤ PRD.89.012001



➤ NPB 887.276: NNPDFpol1.1 prediction with STAR 200 GeV data ($0.8 < \eta < 2.0$)



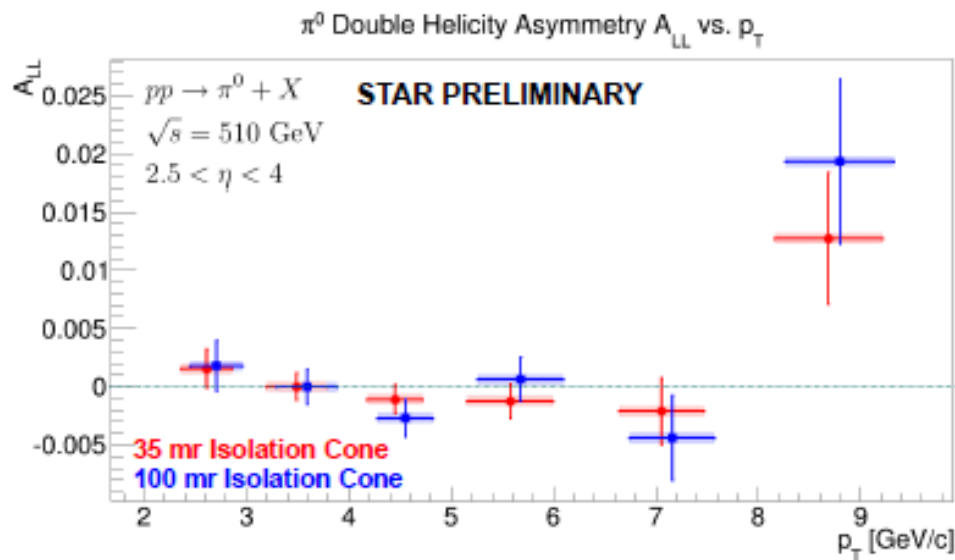
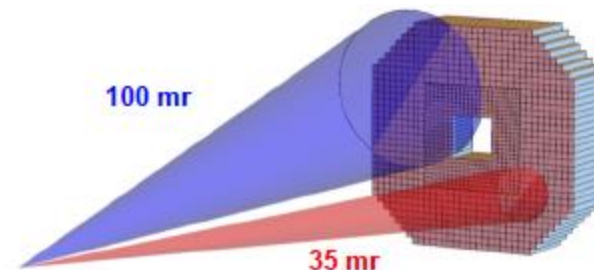
- Will achieve much greater precision with 510 GeV data that are currently being analyzed
 - Higher \sqrt{s} also pushes the sensitivity to lower x_g



π^0 Measurements at Further η Region

➤ C. Dilks for the STAR Collaboration, SPIN 2014

- π^0 measured in FMS at $2.5 < \eta < 4.0$ by using 2012 and 2013 510 GeV data
- Isolated π^0 measured by 2- γ isolation cone with cone radius 35 mr and 100 mr
- A_{LL} of isolated π^0 calculated



- A_{LL} not dependent on isolation cone cut (in contrast transverse asymmetry A_N depends on isolation cone cut, see more details in Mriganka's talk)
- Isolated π^0 A_{LL} consistent with zero
 - Constant fit to isolated π^0 A_{LL} :
 - 35mr cut: $A_{LL} = -2.5 \times 10^{-4} \pm 6.5 \times 10^{-4}$ with $\chi^2/NDF = 7.8/5$
 - 100mr cut: $A_{LL} = -3.3 \times 10^{-4} \pm 8.4 \times 10^{-4}$ with $\chi^2/NDF = 7.8/5$
- The same features in isolated π^0 A_{LL} vs. $E_{\gamma\gamma}$
- Inclusive π^0 A_{LL} currently under investigation

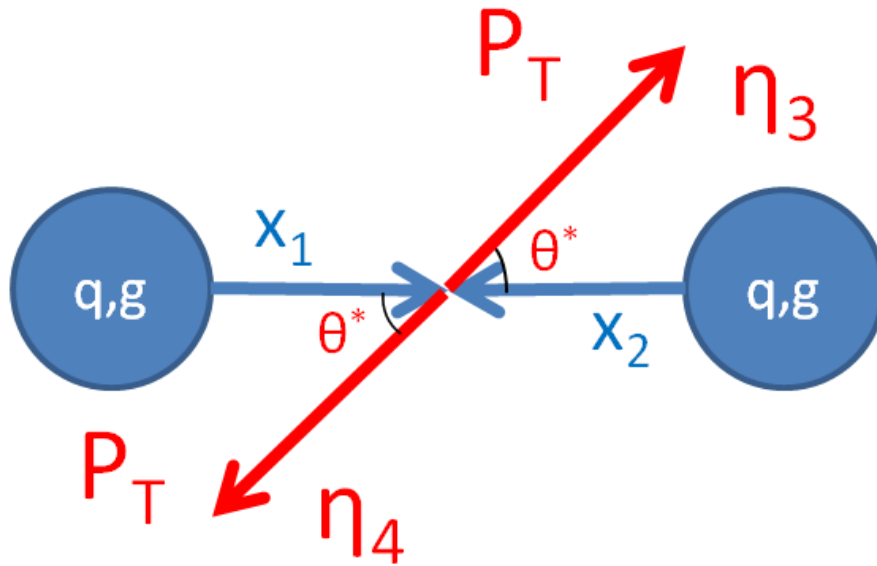
☐ Inclusive jet measurements

☐ π^0 measurements

☒ **Di-jet measurements**



Di-jet Measurements at STAR



$$x_1 = \frac{1}{\sqrt{s}} (p_{T,3} e^{\eta_3} + p_{T,4} e^{\eta_4})$$

$$x_2 = \frac{1}{\sqrt{s}} (p_{T,3} e^{-\eta_3} + p_{T,4} e^{-\eta_4})$$

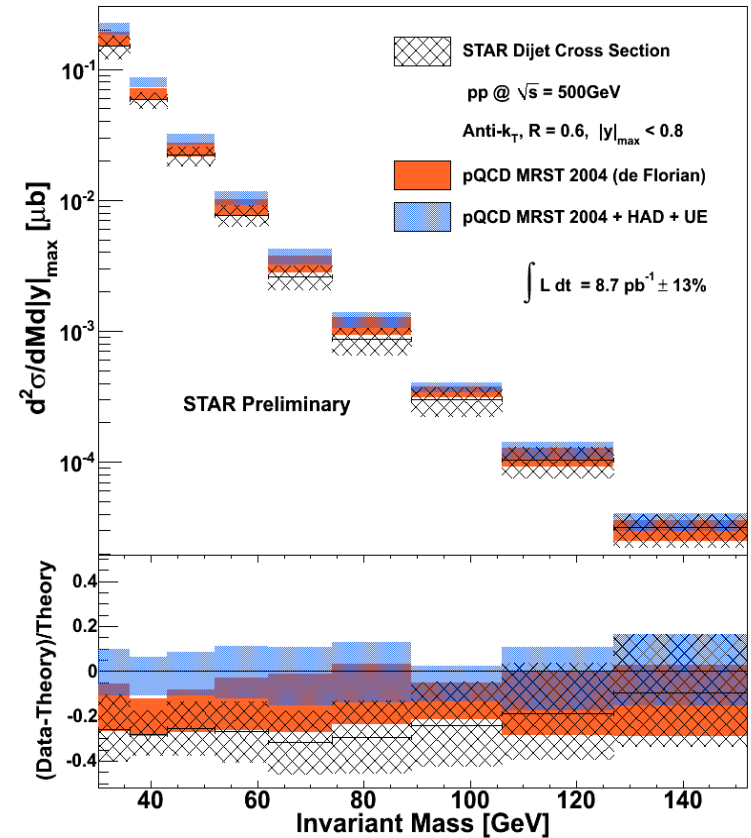
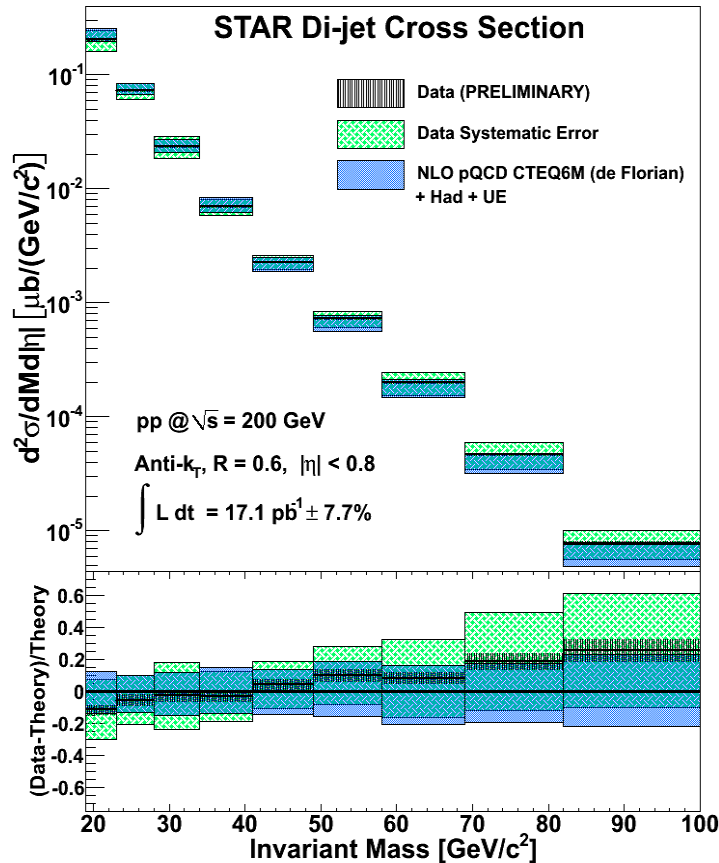
$$M = \sqrt{x_1 x_2 s}$$

$$y = \frac{1}{2} \ln \frac{x_1}{x_2} = \frac{\eta_3 + \eta_4}{2}$$

$$|\cos \theta^*| = \tanh \frac{|\eta_3 - \eta_4|}{2}$$

- Di-jets permit event-by-event calculations of x_1 and x_2 at leading order
- Use the same technique to reconstruct di-jets as the inclusive jets

Di-jet Cross Section at 200 GeV and 500 GeV

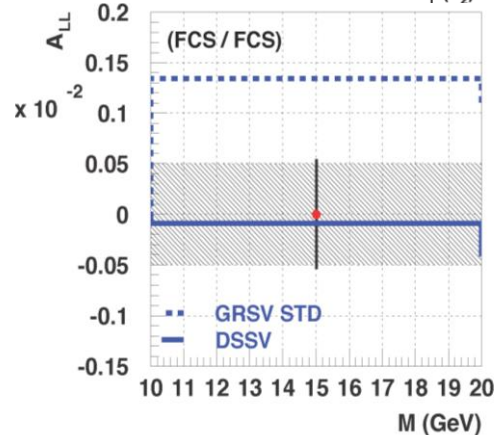
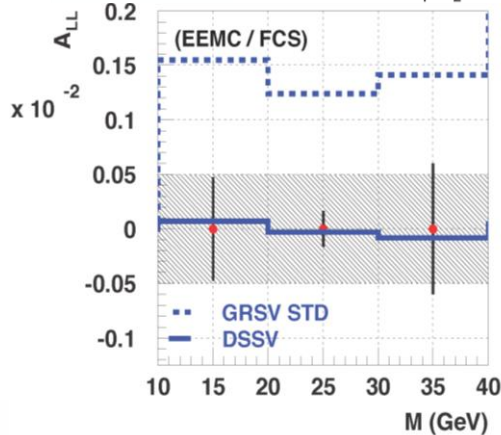
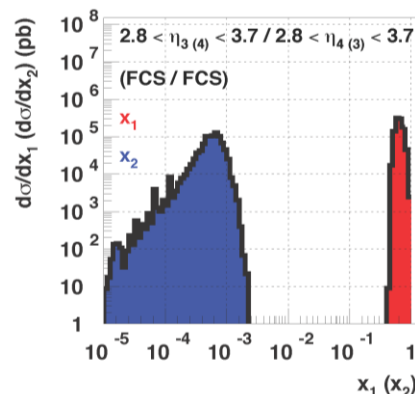
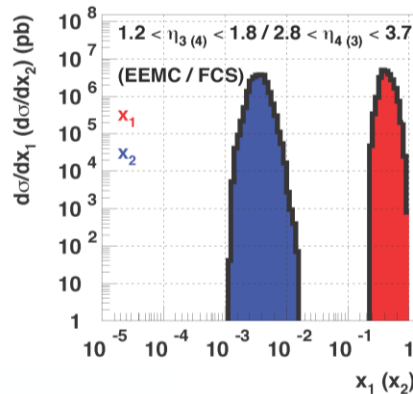


- Di-jet cross section is well-described by NLO pQCD with corrections for hadronization and underlying event
- Will have A_{LL} for 2009 di-jets at 200 GeV soon
- Also analyzing A_{LL} for di-jets at 510 GeV using data from 2012 and 2013



Di-jets in Further Future

- STAR is planning to install a **Forward Calorimeter System (FCS)** in ~2020
- This will enable di-jet measurements with one or both jets in the **forward** region ($2.8 < \eta < 3.7$)
- FCS will provide information about gluon polarization at
 - a) $x \sim 5 \times 10^{-3}$ with **FCS-EEMC** di-jets
 - b) $x \leq 10^{-3}$ with **FCS-FCS** di-jets



- $\sqrt{s} = 500$ GeV
 - Cone Algorithm, $R = 0.7$
 - $E_{T,3} > 5$ GeV, $E_{T,4} > 8$ GeV
-
- Assumed integrated luminosity: 1000 pb^{-1}
 - Assumed polarization: 60%

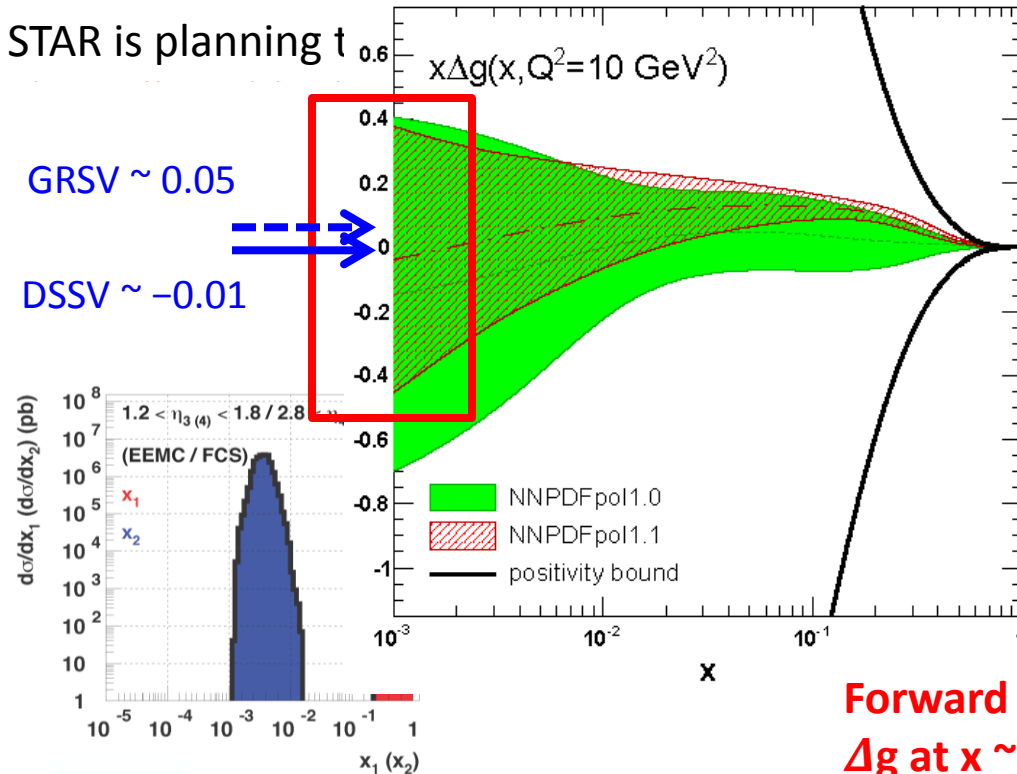


Di-jets in Further Future

- STAR is planning t

GRSV ~ 0.05

DSSV ~ -0.01



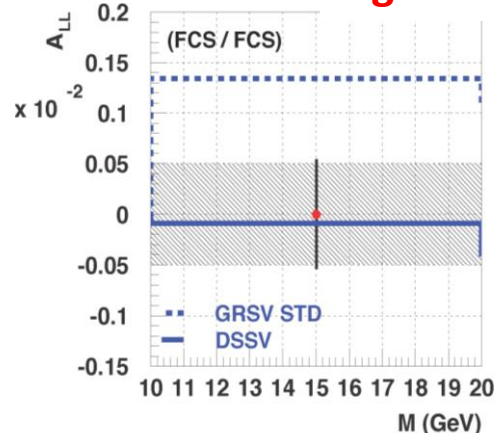
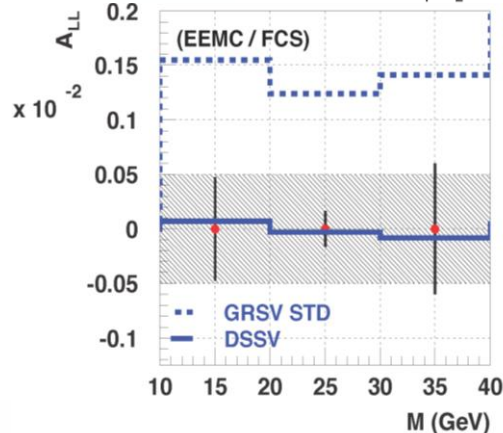
em (FCS) in ~ 2020

1 jets in the **forward** region

at

- $\sqrt{s} = 500$ GeV
- Cone Algorithm, $R = 0.7$
- $E_{T,3} > 5$ GeV, $E_{T,4} > 8$ GeV

Forward di-jets will further constrain Δg at $x \sim 10^{-3}$



- Assumed integrated luminosity: 1000 pb^{-1}
- Assumed polarization: 60%



Conclusion

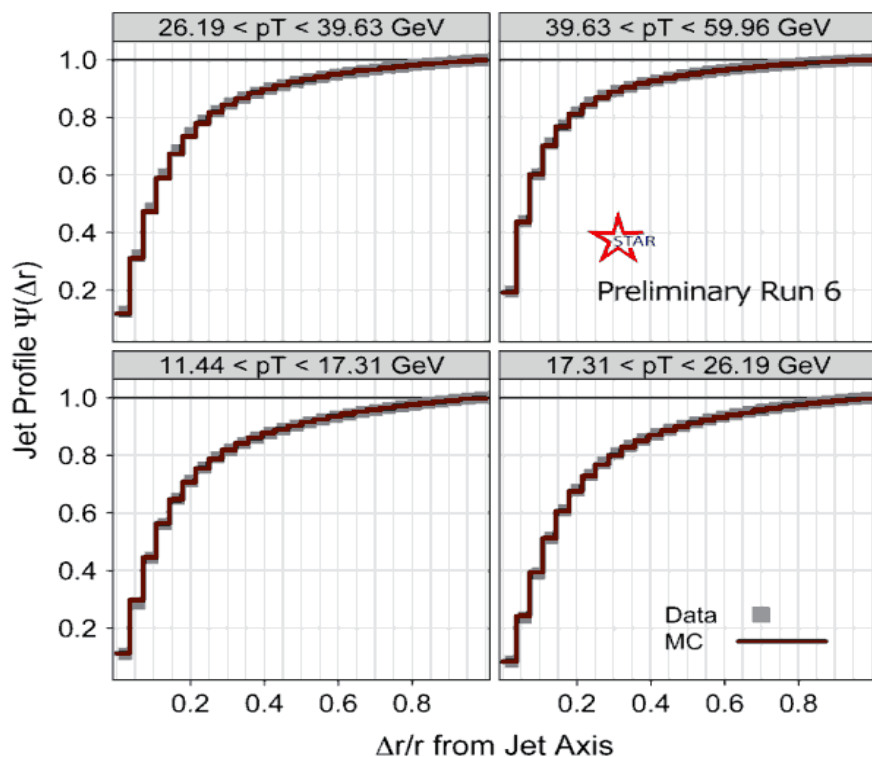
- STAR **inclusive jet, π^0 , and di-jet A_{LL}** measurements are **unique** to explore gluon contribution to proton spin
- STAR 2009 inclusive jet A_{LL} results provide the first experimental evidence for **positive gluon polarization** in the RHIC range
- STAR 2012 510 GeV inclusive jet A_{LL} results extend measurements at **lower x_g** and **agree well** with STAR 2009 200 GeV data in the overlapping x_T range
- More results coming up in the near future
 - **First measurements:**
 - Di-jet A_{LL} at 200 GeV (2009)
 - Di-jet A_{LL} at 510 GeV (2012 and 2013)
 - Inclusive π^0 A_{LL} at 510 GeV (2012 and 2013)
 - **Improved precision for:**
 - Inclusive jet A_{LL} at 200 GeV (2015)
- In the further future, STAR will use **forward di-jets** to explore gluon polarization at very **low x_g ($\sim 10^{-3}$)**



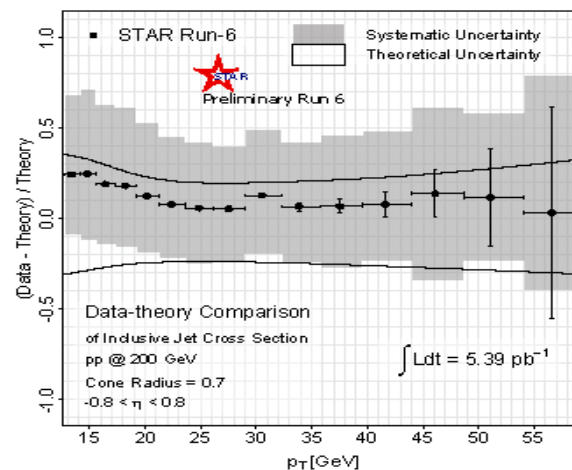
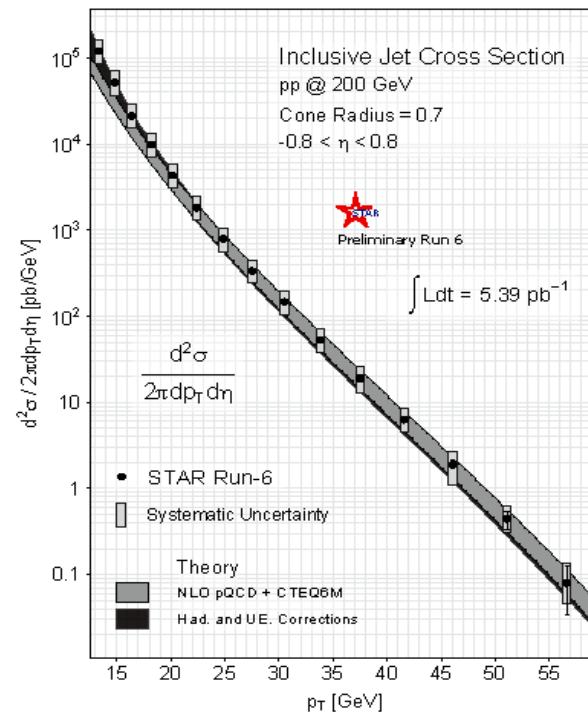
Back Up



Inclusive Jet Cross Section from 2006 Data

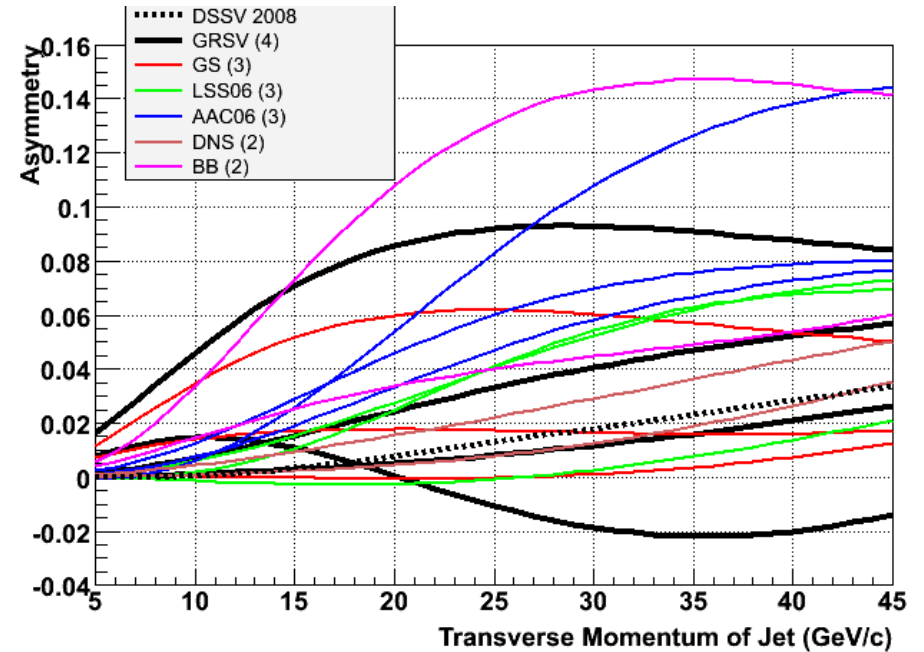
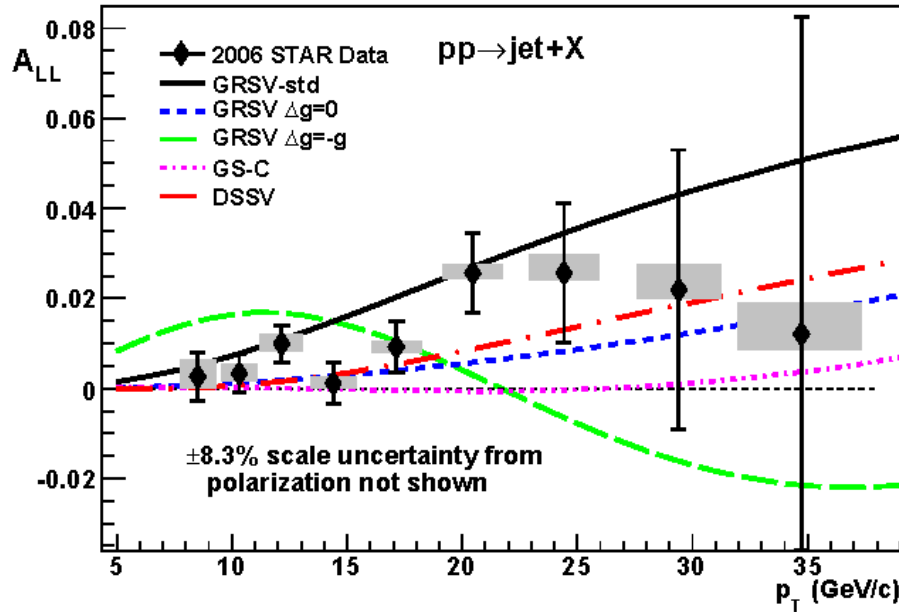


- Good agreement between data and simulation
- Good agreement with NLO pQCD calculation after hadronization and underlying event correction is applied
- Jet production is well understood at RHIC energies



Inclusive Jet A_{LL} from 2006 Data

➤ PRD 86, 032006



- STAR inclusive jet A_{LL} from 2006 excluded those scenarios that had a large gluon polarization within the accessible x region

